2017 AAS GN&C Conference

“Narrowband Rejection of Reaction Wheel and Environmental Disturbances for the WFIRST CGI OMC Testbed”

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WFIRST Mission (In Phase A: Preliminary Analysis)

<u>The Science</u>:

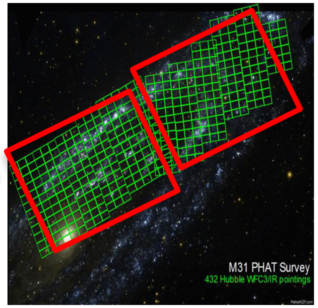
- Answer basic questions about **dark energy** and cosmic acceleration using weak gravitational lensing, supernova distances, BAO.
- Complete a census of exoplanets using gravitational microlensing
- Coronagraph for **<u>DIRECT IMAGING</u>** of exoplanets!!!

WFIRST -> Wide Field InfraRed Survey Telescope. Flagship NASA mission, $1.6 Billion.

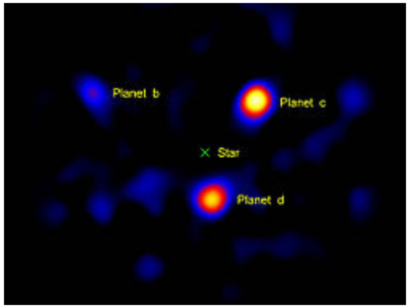
- **Number 1 priority of the Astro2010 New Worlds, New Horizon Decadal Survey of Astronomy and Astrophysics**. Expected launch in mid 2020s.
- Hubble like telescope (2.4m primary mirror) was donated from NRO.
- Two instruments:

  1.) WFI (Goddard) 288 Mpixel HgCdTe NIR 0.7-2.0 um detector. 100 times bigger FOV than Hubble with the same resolution. Two spectrographs. **<u>Requires 20 mas RMS pointing error</u>**

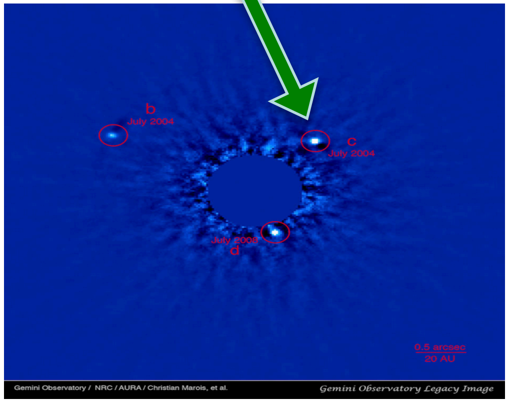
  2.) CGI (JPL), 0.4-1.0um high contrast coronagraph with 1 part per billion suppression of starlight. Enables detection of planets within 0.1 asec or 3λ/D of their host stars. **<u>This drives pointing requirement for the coronagraph to 0.4-0.8 mas RMS</u>**



The HST/WFC3/IR PHAT Survey required 432 pointings to cover M31 while only 2 WFIRST pointings are required
* From WFIRST website

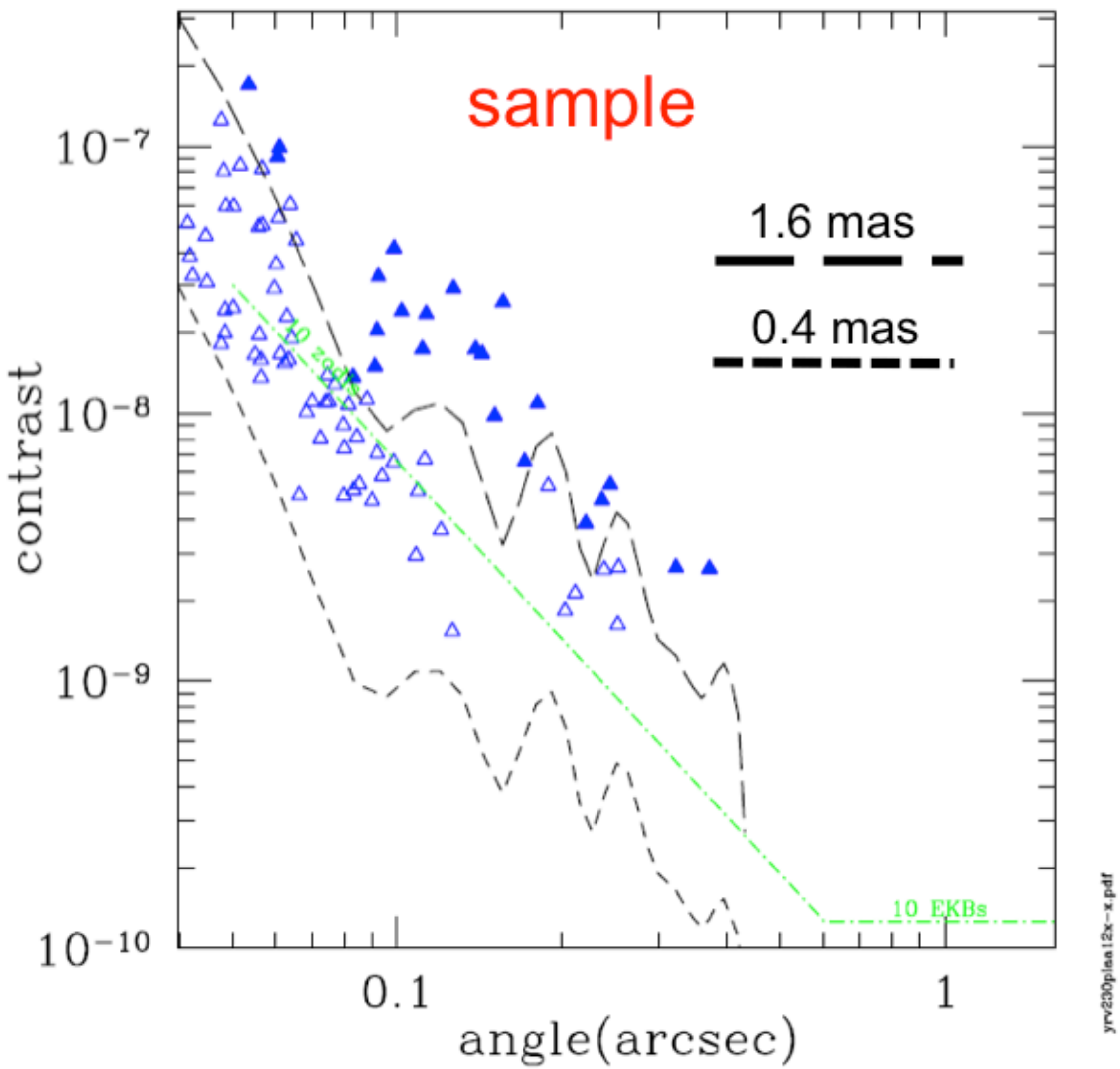


Hale telescope image of HR8799 exosolar system in the constellation Pegasus. Image taken using the vortex coronagraph at Palomar.



Exoplanet Detection and Pointing Performance

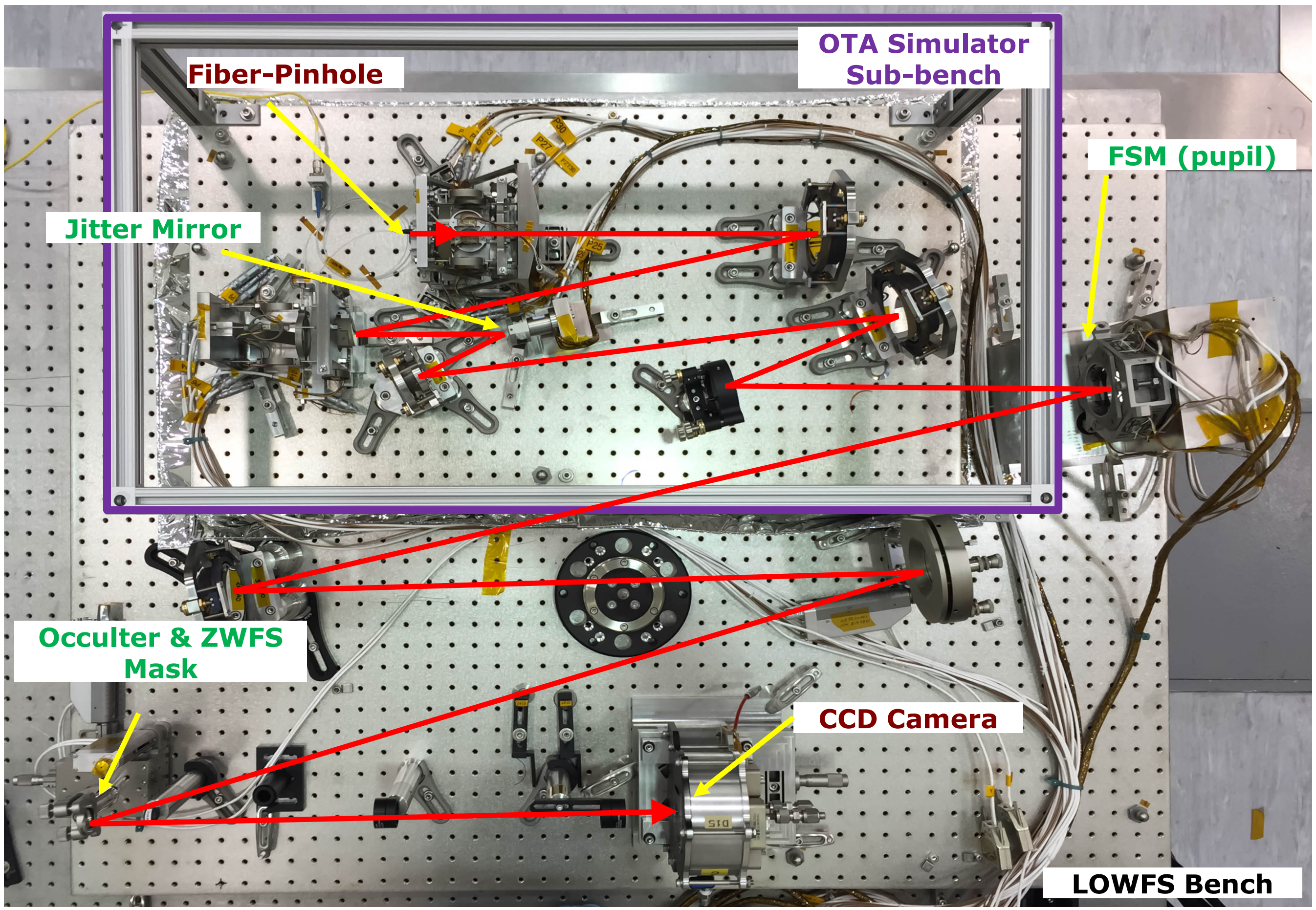
- Coronagraph pointing performance is critical to science return! More science targets are observable with better pointing.



Legend:
- Dotted lines represent contrast achievable with the stated pointing performance
- Triangles represent known target star/planet contrasts

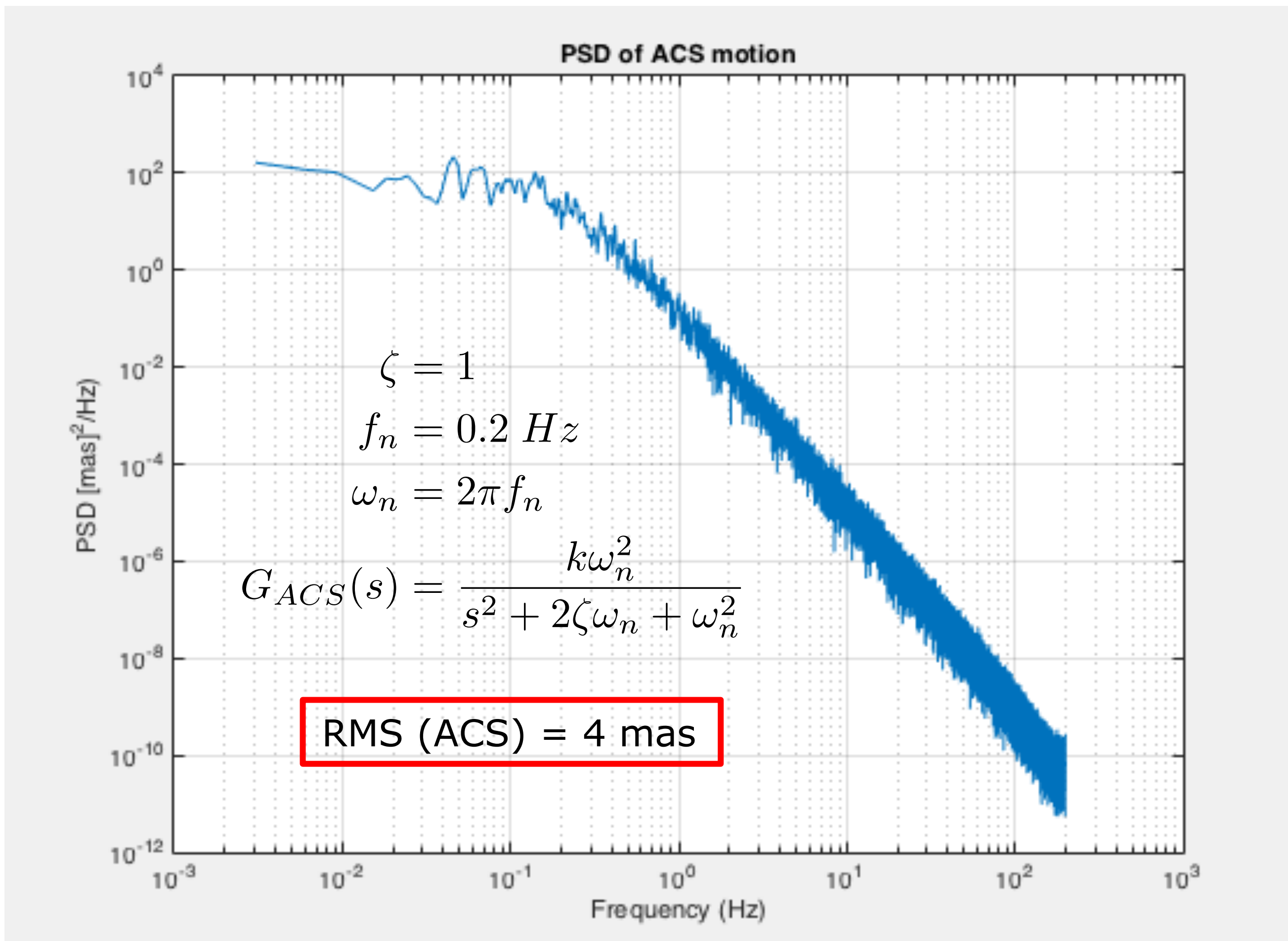
LOWFS/C Testbed at JPL

- The LOWFS/C testbed injects LOS and higher order wavefront abberations.
  - OTA assembly used to inject high order WFE
  - Jitter mirror (JM) used to inject LOS disturbances (ACS and RWA Cycle 5)
  - FSM used to suppress LOS disturbances
- LOWFS Z2 and Z3 camera measurements, RWA “tachometer” and harmonic coefficient knowledge is used by the LOS control system to suppress LOS disturbances.



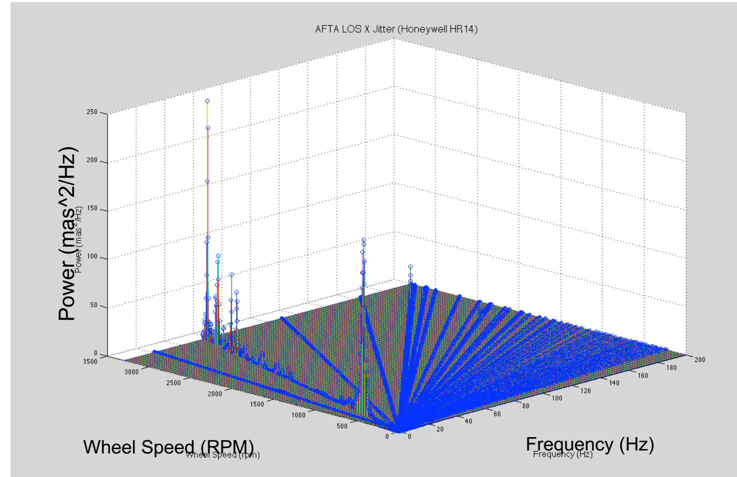
Injected Disturbance: ACS LOS

- Per Goddard ACS team. 4 mas per axis OTS. (Requirement is 14 mas for the WFI instrument.)
  - Star tracker and IMU attitude estimates aided with WFI measurements to achieve 4 mas.
  - Capability to scale this disturbance up or down is provided by the JM signal generator.

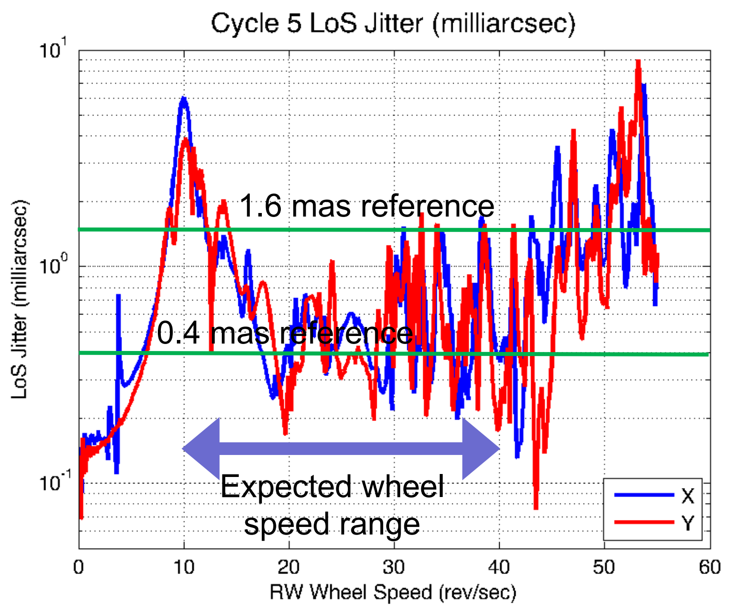


Injected Disturbance: RWA LOS

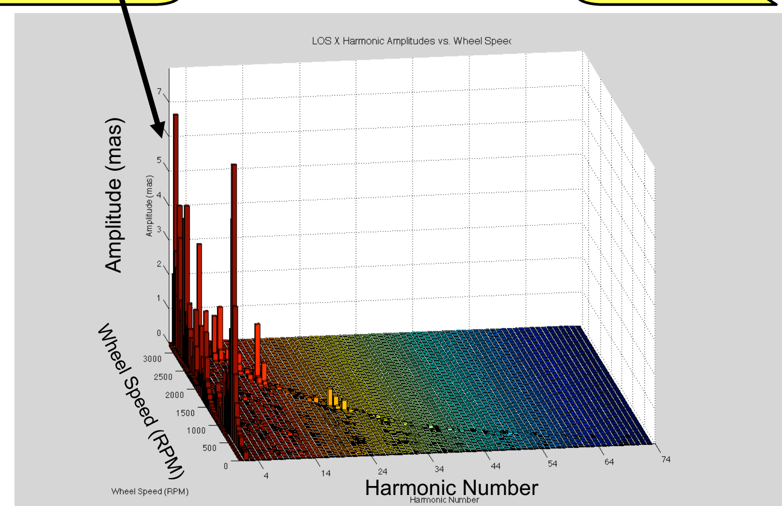
- RWA LOS disturbance model based on “Cycle 5” deliverable from Goddard. MUF included.
  - RWAs are Honeywell HR14 with 75 N-m-s momentum capacity.
  - Only one of the 4 wheels is used
  - Spec sheet imbalances are 0.48 gram-cm (static) and 13.7 gram-cm^2 (dynamic)
  - Harmonic model includes 73 harmonics with 1 subharmonic at 0.348.



$$LOS_{X or Y}(t) = \sum_{i=1}^{N_h} f_i(\Omega(t)) \sin(2\pi h_i \Omega(t) t + \alpha_i)$$



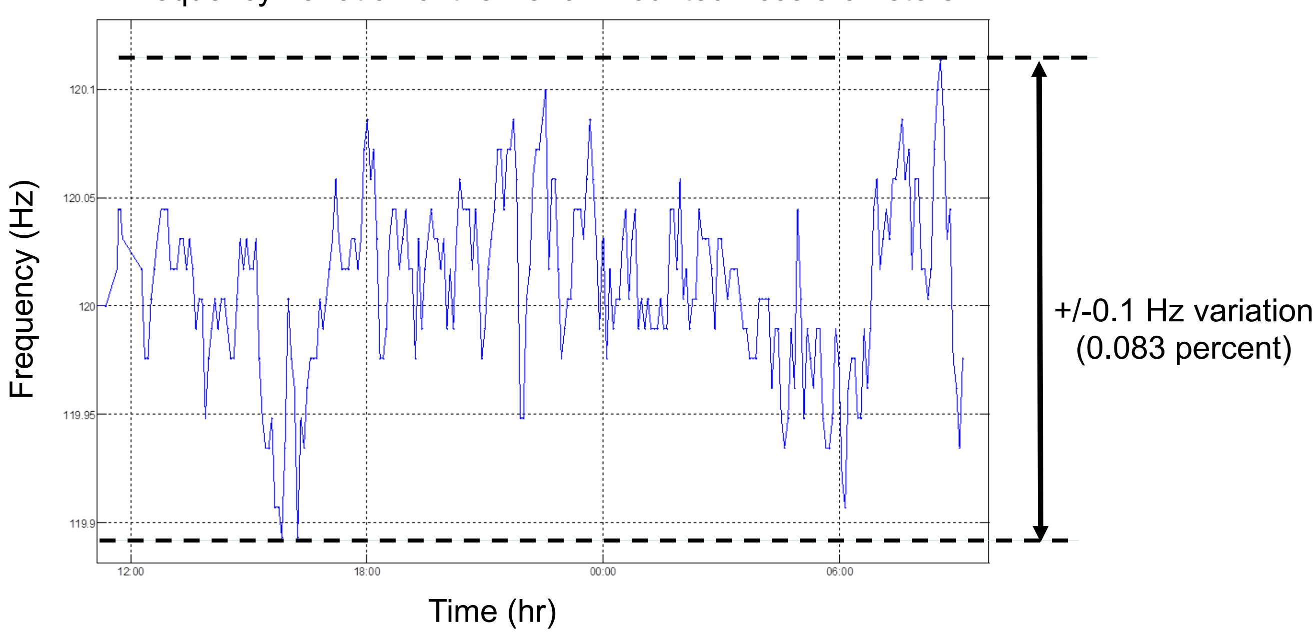
Most of the energy is in the first two harmonics. (Sub. and fundamental)



Environmental Disturbance: Line Noise

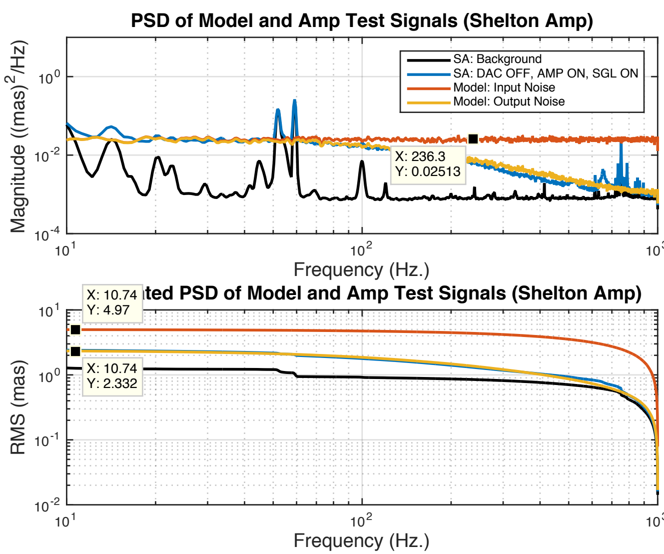
- Evidence that the line noise is real motion and not sensor noise:
  1.) It is observed in three sensors, the science camera, the LOWFS camera and bench mounted accelerometers.
  2.) Cameras are somewhat immune to line noise.
  3.) Disturbance is correlated with the building temperature (i.e. the air handling activity) which is consistent with the hypothesis that the HVAC system is causing a percussive force on the vacuum chamber. Cabling defeats the optical bench isolator.
  4.) The 120 Hz disturbance occurs on only one of the camera channels not both as you would expect if it was an electrical noise issue.
  5.) The accelerometers on the optical bench measure vertical motion the bench which is consistent with the disturbance being larger in the Z2 camera measurement channel.

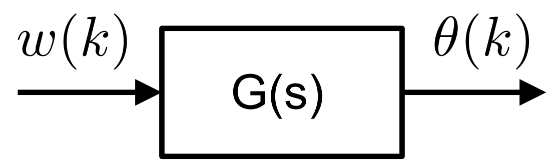
Frequency Variation of the Bench Mounted Accelerometers



FSM Actuator PZT Model

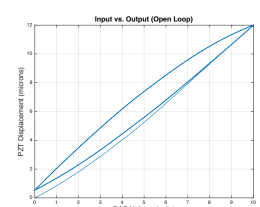
- Vacuum chamber data gave the response from sensor noise to PZT displacement, or the complementary sensitivity TF. With this known and amp TF given, the gains in the PI compensator can be solved for giving the correct loop shape for the model.
- NOTE: DAC input voltage was attenuated by 1/100 using an input stage op-amp. This compromised the +/-82 arc. sec. stroke of the FSM but was necessary to reduce DAC noise jitter.

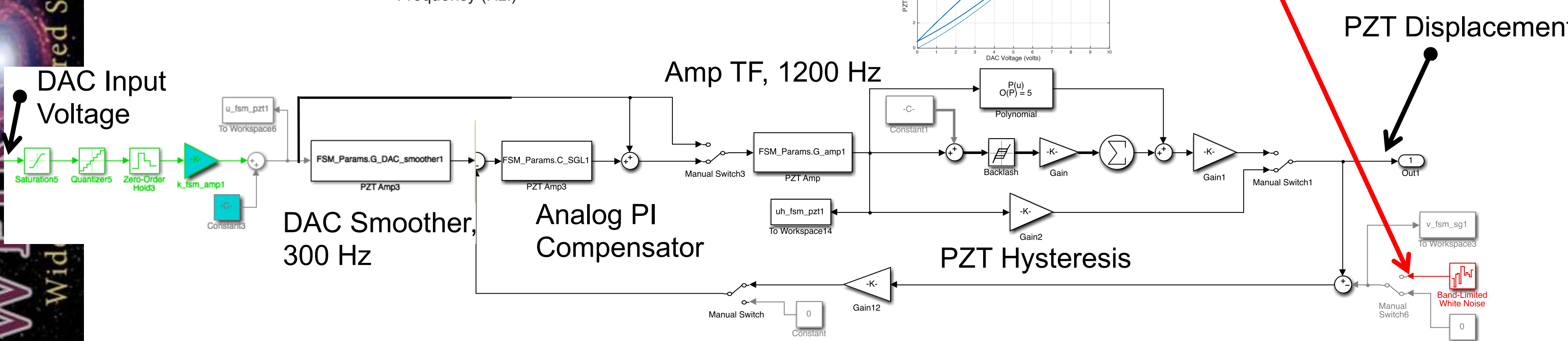




$$G(s) = \frac{(1/(2\pi \cdot 700))s + 1}{(1/(2\pi \cdot 150))s + 1}$$

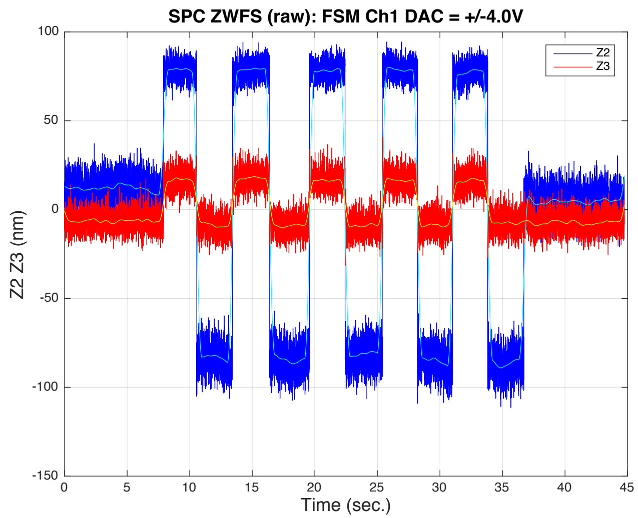
$$w(k) \in N(0, 5\,(mas))$$





Optical Sensitivity and Camera Noise Calibrations

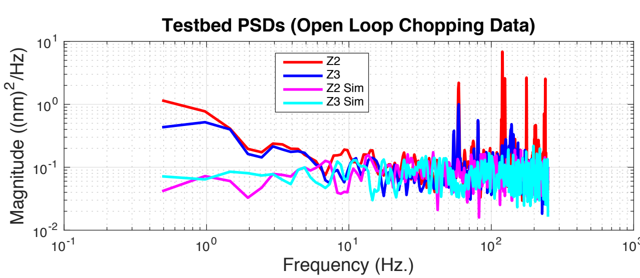
- Each PZT on the FSM and JM were moved and the optical measurements were recorded. Optical sensitivities from the PZT displacements to camera wavefront measurements can be generated from this data.

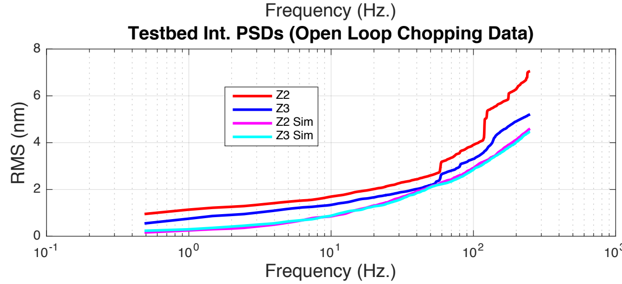


Sensitivity Matrices: (Units are nm per m of PZT motion)

$$\mathbf{S}_{FSM}^{optical} = \begin{bmatrix} 2.458e9 & -1.661e9 & -0.796e9 \\ 0.361e9 & -1.341e9 & 0.980e9 \end{bmatrix}$$

$$\mathbf{S}_{JM}^{optical} = \begin{bmatrix} 1.632e9 & 3.126e9 & -4.758e9 \\ -1.873e9 & 2.850e9 & -0.977e9 \end{bmatrix}$$



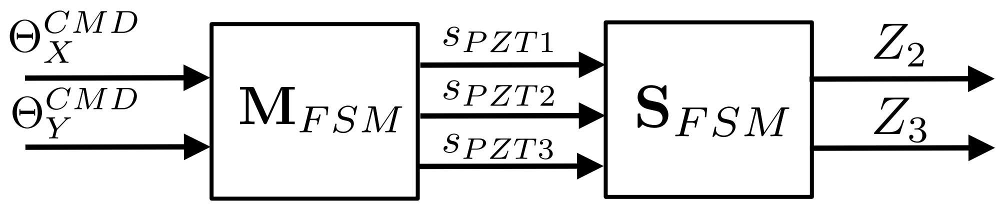


Noise floor of these PSDs gives the photon noise of the camera measurements:

Z2 RMS = 4.6 nm
Z3 RMS = 4.4 nm

FSM Workspace and Steering

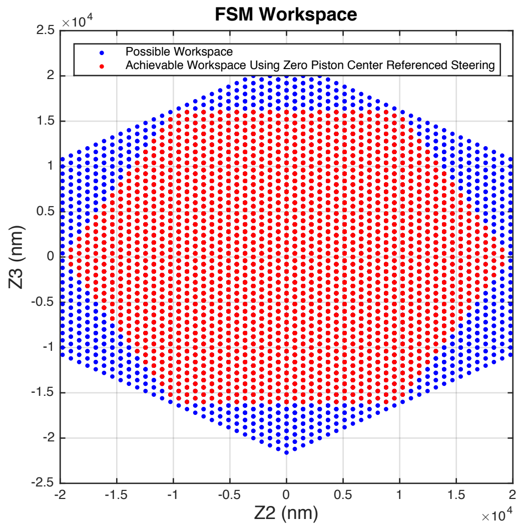
- FSM steering method should:
  1.) Decouple/diagonalize the input/output relationship from the tip/tilt commands to the zernike measurements.
  2.) Fully utilize the available (hexagonal) workspace. Important since the spacecraft ACS is being used to desaturate the FSM stroke.



$$\mathbf{M}_{FSM} = \mathbf{S}_{FSM}^T(\mathbf{S}_{FSM} \cdot \mathbf{S}_{FSM}^T)^{-1}$$

$$\mathbf{S}_{FSM} \cdot \mathbf{M}_{FSM} = \mathbf{I}$$

PZT amplifier dynamics are between M and S but the BW of the strain gauge loops is > 300 Hz



Using $\mathbf{M}_{FSM}$ is a "*zero piston center based steering method*". This does not preserve the entire available workspace. Piston of the optic must be allowed to take advantage of the entire workspace.

$$\min(\max([s_{PZT1} \quad s_{PZT2} \quad s_{PZT3}]))$$

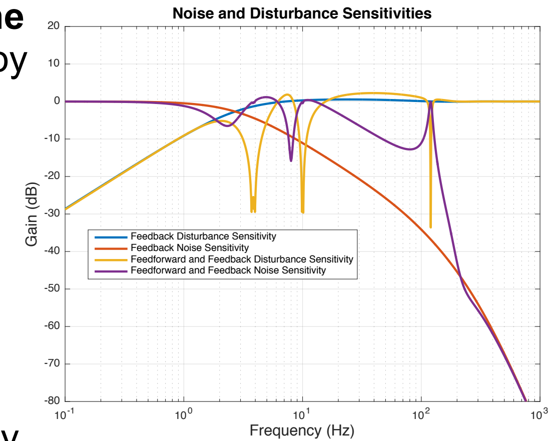
Simple numerical procedure was developed to solve the above optimization problem. Resulted in achieving full workspace.

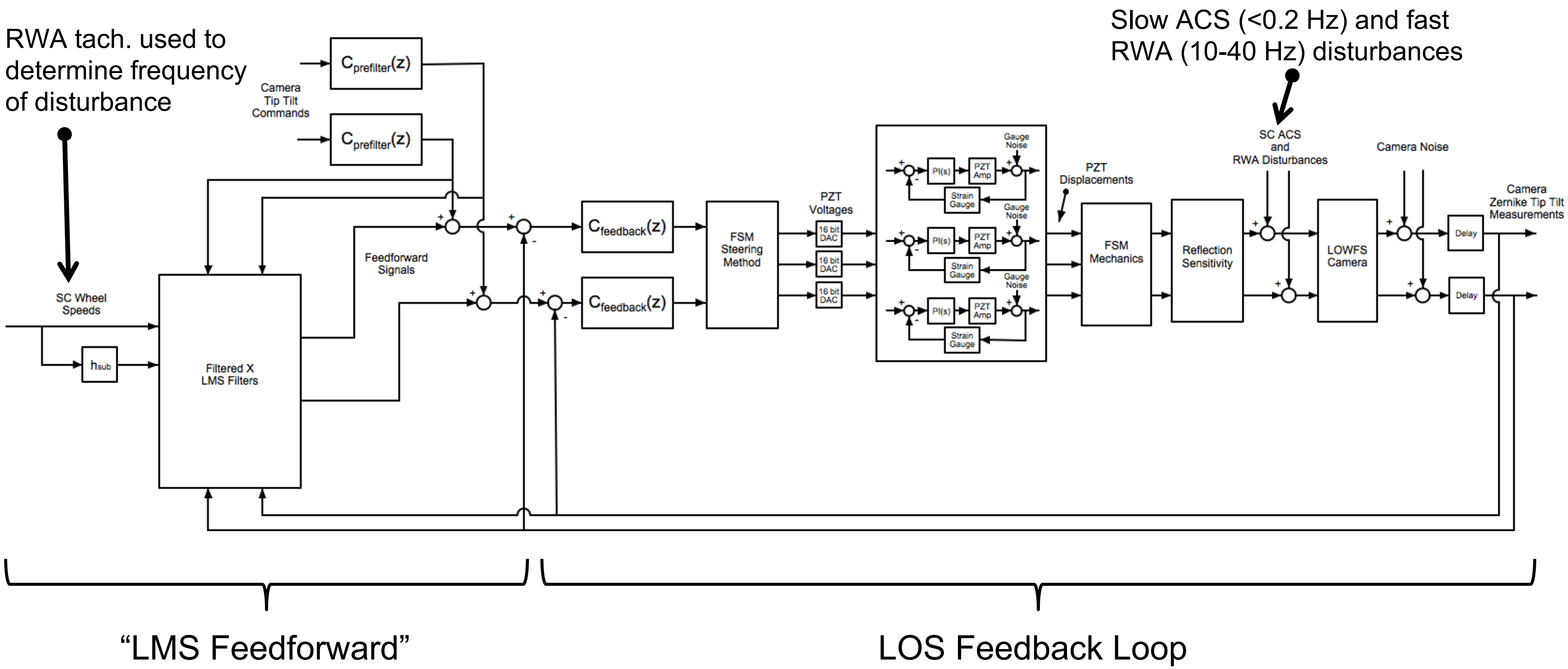
Coronagraph LOS Control: Feedback and Feedforward

- Feedback: The LOS loop is shaped for **optimal rejection of the ACS disturbance and LOWFSC sensor noise.** This is done by balancing the error contribution from both sources of jitter.

  Feedforward: RWA tones are attenuated using an LMS filter which sends commands to the feedback loop. LMS estimates the gain and phase of the disturbance. RWA tachometer signal used to determine the frequency of the disturbance.

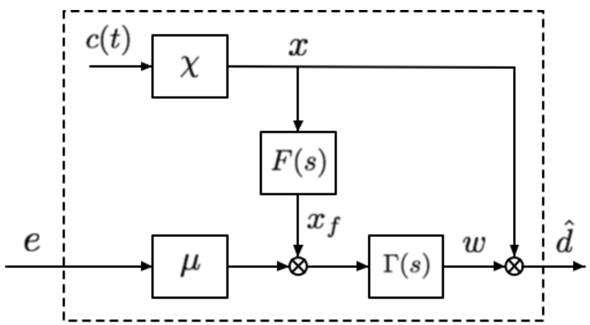
- Allows one to have the best of both worlds, low bandwidth to reject sensor noise and feedforward to reject the high frequency tones.





LMS as Ringer

- LMS is nothing more than a LTI ringer (high gain) at the regressor frequencies.
  - This follows from the properties of modulation and demodulation*.

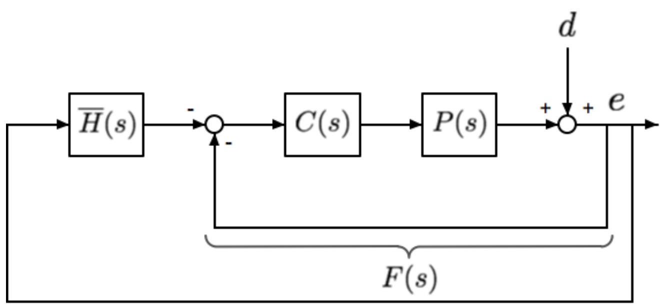


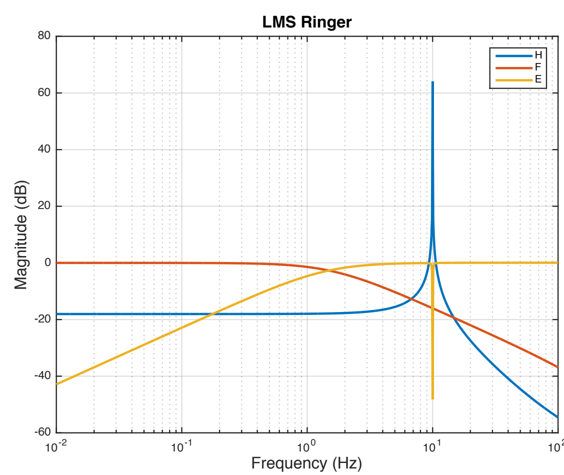
$$\hat{d} = \overline{H}(s)e \qquad \overline{H}(s) = \mu \sum_{i=1}^{m} d_i^2 H_i(s)$$

$$\boxed{H_i(s) = \frac{F_{Re}(\omega_i)}{2}\left(\Gamma(s - j\omega_i) + \Gamma(s + j\omega_i)\right) + \frac{F_{Im}(\omega_i)}{2}\left(\Gamma(s - j\omega_i) - \Gamma(s + j\omega_i)\right)}$$

$$\overline{H}(s) = \mu d_1^2 \frac{F_{Re}(\omega_1)s + \left(F_{Re}(\omega_1)\alpha + F_{Im}(\omega_1)\omega_1\right)}{s^2 + 2\alpha s + (\omega_1^2 + \alpha^2)}$$

- An example with F(s) as the LOS feedback loop and the gradient algorithm with leakage …





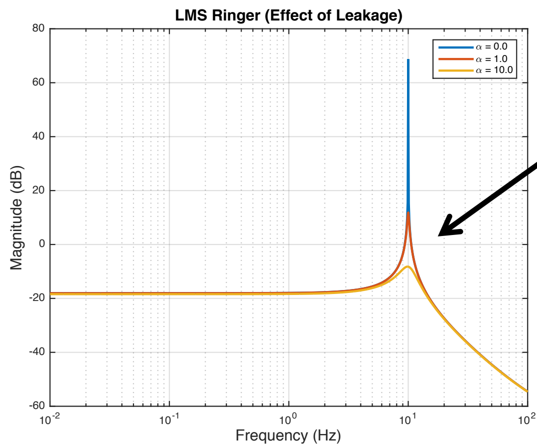
$$\Gamma(s) = \frac{1}{s + \alpha}$$

$$e = \underbrace{\frac{1}{1 + F(s)\overline{H}(s)} \frac{1}{1 + C(s)P(s)}}_{E(s)} d$$

* Bayard, Dave, *"A General Theory of Linear Time-Invariant Adaptive Feedforward Systems with Harmonic Regressors"*, IEEE Transactions on Automatic Control, Vol. 45, No. 11, Nov. 2000.

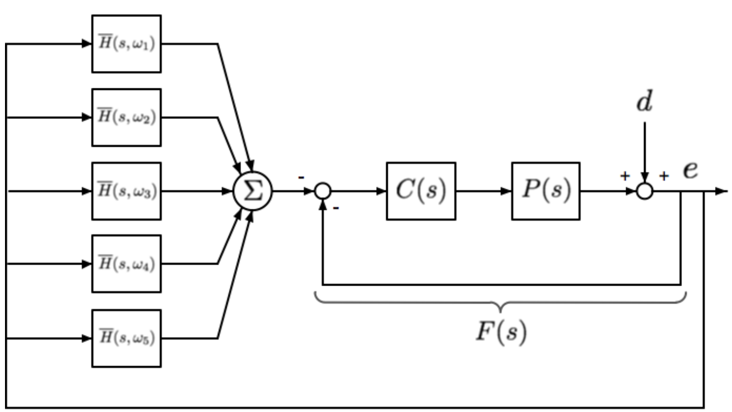
Robust LMS: Dealing with Tach. Uncertainty

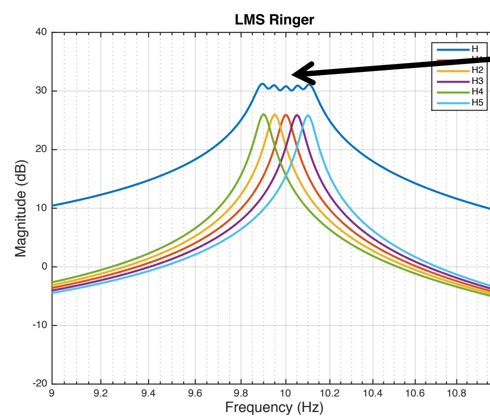
- One issue is that the wheel speed tachometer and line frequency estimate will be in error to some extent resulting in incorrect placement of the LMS ringer. <u>Tachometer errors greater than 0.1% degrades performance</u>.
  - Adding leakage actually does not "broaden" the ringer …



The ringers with more leakage are contained within the ringer with zero leakage. [i.e. performance robustness to wheel speed uncertainty is <u>**not improved**</u>.]

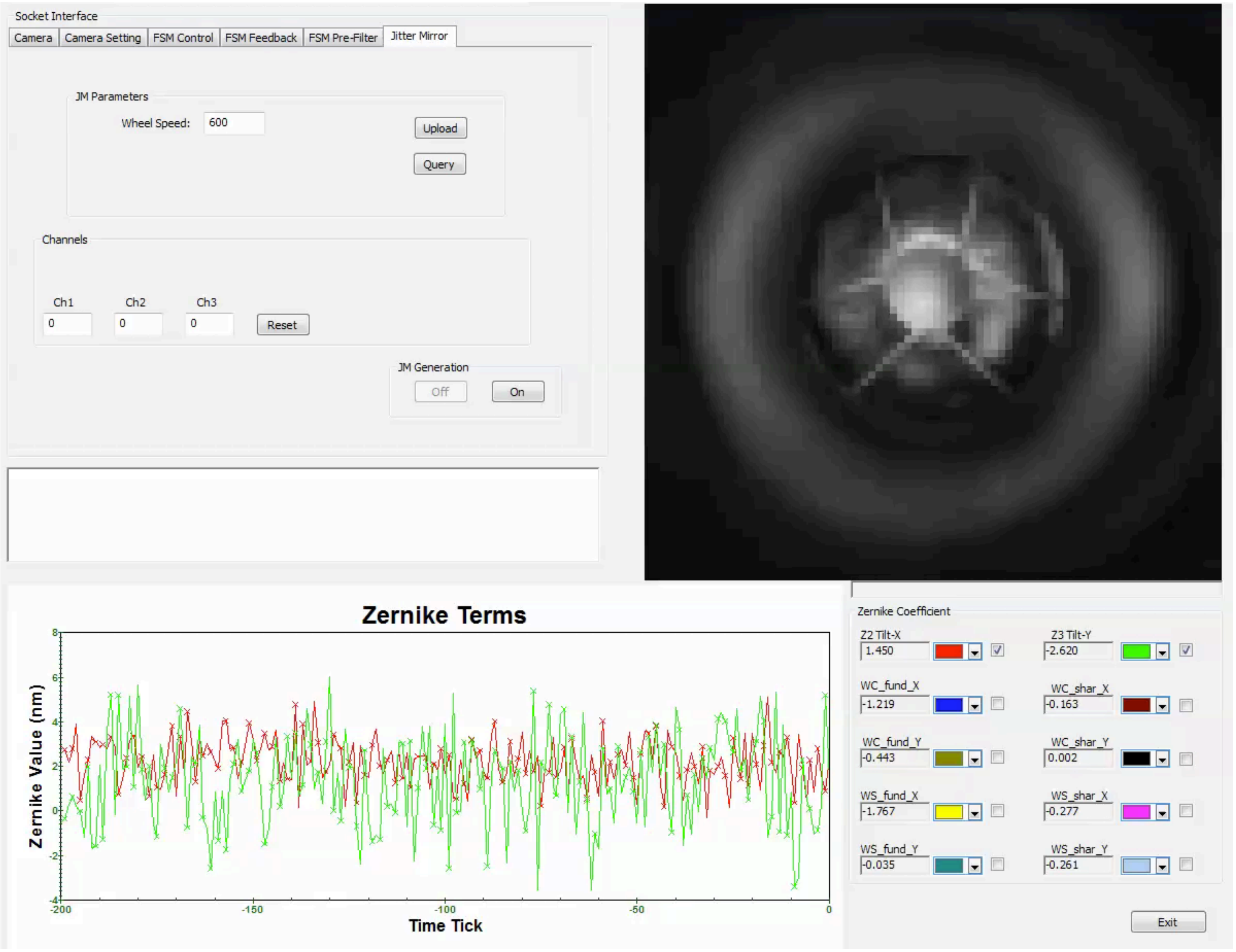
- One alternative is to robustify the performance using a **parallel combination** of LMS filters each with a slightly different regressor frequency. Produces a "flat-top" response which makes the performance uniform even with frequency uncertainty.





"Flat-top"

Testbed Movie



OMC Testbed PSDs

- Open loop, closed loop with feedback, and closed loop with feedback and feedforward PSDs.
  - Three tones killed: RWA subharmonic, RWA fundamental and environmental tone at 120 Hz attenuated.
- These PSDs are of the measured jitter, the actual/true jitter will be less because the complementary transfer function has limited BW.